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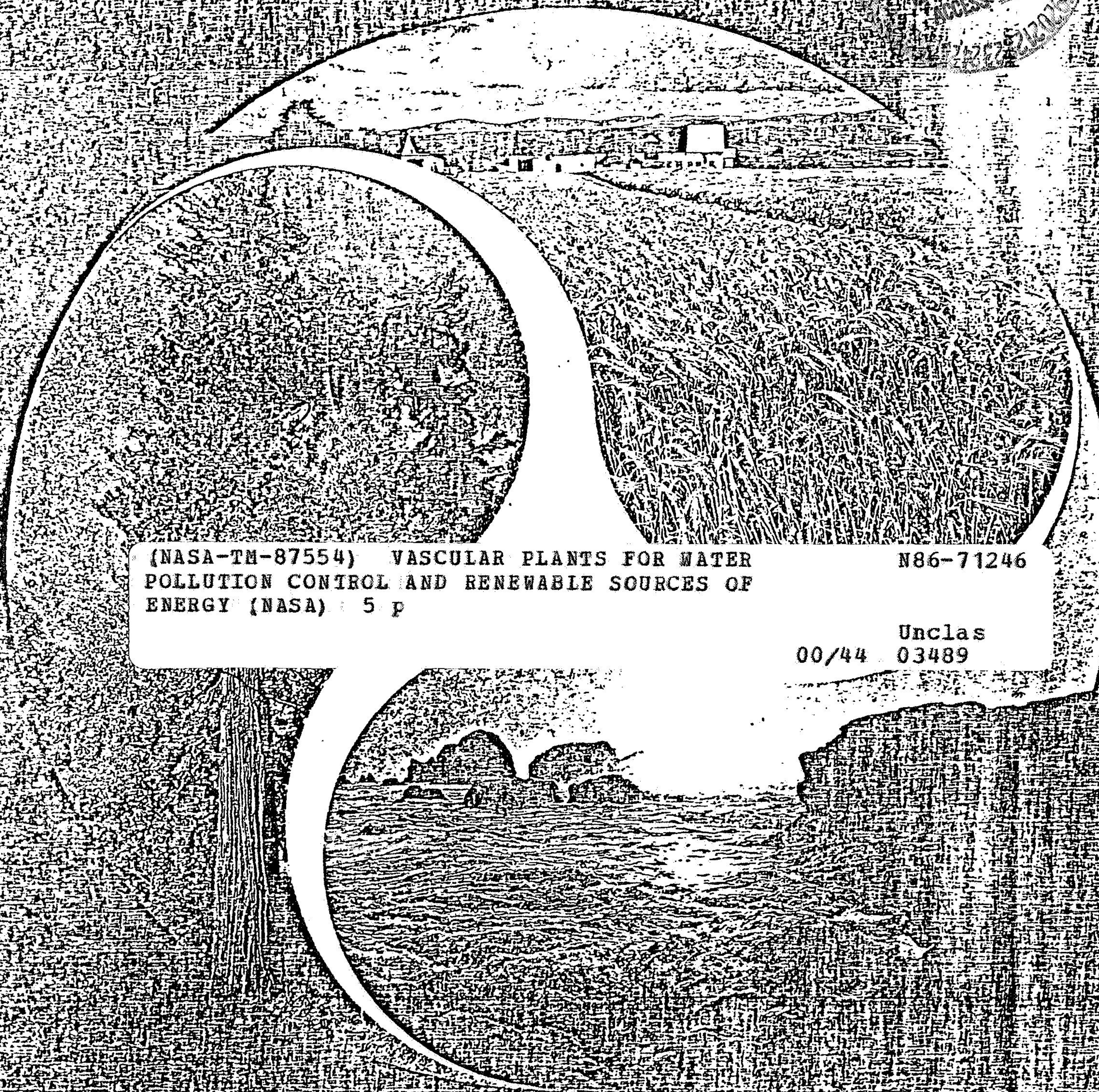

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Vascular Plants for Water Pollution Control and Renewable Sources of Energy

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Vascular aquatic plants have demonstrated their ability to remove pollutants from domestic and chemical wastewaters. Plants such as the water hyacinth (Eichhornia crassipes), duckweed (Lemna sp., Spirodela sp., and Wolffia sp.), and cattail (Typha sp.) thrive in nutrient-rich waters and produce tremendous quantities of biomass under favorable climatic conditions. This method of wastewater treatment is currently being used exclusively at NASA's National Space Technology Laboratories (NSTL) with water hyacinths and duckweed to treat daily over 759 m³ of domestic wastewater and 114 m³ of chemical wastewater in four separate systems. The harvested plants from these systems have been used in various biomass utilization projects over the past five years. In laboratory batch studies of digesting vascular plants with anaerobic filters, NASA has found that 140-280 liters methane per kg dry weight can be obtained in an average of 23 days. Current NASA projects at NSTL seek to expand the technology required to design energy systems which produce methane through bioconversion with anaerobic filters and use the mineral residue as a nutrient source for producing new biomass.

Introduction

The science of treating wastewater with a combination of microbiological and photosynthetic organisms and converting the new biomass into products which can be directly recycled into the environment is a rapidly expanding field. The water hyacinth (Eichhornia crassipes), duckweed (Lemnaceae), and water pennywort (Hydrocotyle ranunculoides) are among the floating, emergent vascular aquatic plants that are currently being used for wastewater treatment (1,2,3). Studies with rooted, emergent vascular aquatic plants such as bulrush (Shoenoplectus lacustris), reeds (Phragmites communis), and cattail (Typha sp.) have also shown promising results (4,5). All of the harvested plant material from these systems can be used as a substrate for producing biogas containing an average of 60% methane by volume. The sludge remaining from this process can be recycled into the environment as stabilized organic fertilizer. Numerous advantages can be cited for an integrated system of waste treatment by natural processes and energy production through bioconversion. The major advantages are:

1. A high degree of waste treatment and water reclamation can be achieved.
2. Nutrients are reclaimed from the polluted wastewater in an environmentally safe form (plant biomass).
3. The bioconversion process produces a clean fuel - methane.
4. The bioconversion processes use renewable substrates in the form of fresh plant material.
5. Mineral residue from the bioconversion process can be perpetually recycled as a fertilizer.
6. Bioconversion through anaerobic fermentation is a low temperature and low pressure process.
7. Methane can be stored for later use; whereas solar energy cannot be stored efficiently.
8. Methane can be used in existing hardware.
9. Accidental leaks from biodigesters have no adverse or long term environmental impact such as those associated with oil spills or nuclear accidents.
10. No by-products are generated which require further treatment and/or perpetual storage.
11. Energy farms and biogas production do not alter the heat balance of the earth.

Wastewater Treatment By Natural Processes

The National Aeronautics and Space Administration (NASA) has supported an extensive program at the National Space Technology Laboratories (NSTL) to develop aquiculture wastewater treatment technology as well as energy production techniques which can be used alone or in conjunction with wastewater treatment. The results of the NASA research in the area of aquiculture have been published in a number of reports. In brief, NASA has introduced water hyacinths into four, existing domestic wastewater treatment lagoon systems in south Mississippi. The basic design features of the two, one cell lagoon systems that were totally covered with water hyacinths are consolidated in Table 1 (1,2). These systems were monitored to determine the additional treatment that could be contributed to the water hyacinth. It must be noted here that when the water hyacinth was introduced into these systems a mixture of several species of duckweed and water pennywort were also introduced. In the winter time, these cold tolerant plants became established. However when warm weather returned in the spring, these plants yielded to the highly prolific water hyacinth.

TABLE 1. BASIC DESIGN FEATURES OF THE NASA EXPERIMENTAL SYSTEMS.[1,2]

Lagoon Location	Surface Area, ha	Discharge Flow Rate m^3/day	BOD_5 Loading Rate kg/ha/day
Lucedale, MS	3.6	935	44
NSTL Lagoon #1	2.0	475	26

As seen in Table 2, the water hyacinth upgraded the effluent water quality in the systems to meet a maximum 5-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS) requirement of 30 mg/l each. Due to the results of this research endeavor, NASA at NSTL adapted this technique to upgrade all of its domestic wastewater systems at NSTL. There are three systems at NSTL which daily receive a total of 759 m³ of domestic wastewater.

TABLE 2. MEAN WATER QUALITY OF THE NASA EXPERIMENTAL SYSTEMS BEFORE AND AFTER THE ADDITION OF WATER HYACINTHS.[1,2]

Lagoon Location	WITH Water Hyacinths BOD_5, mg/l Inf	Eff	TSS, mg/l Inf	Eff	WITHOUT Water Hyacinths BOD_5, mg/l Inf	Eff	TSS, mg/l Inf	Eff
Lucedale, MS	161	23	125	6	127	52	140	77
NSTL Lagoon #1	110	5	97	10	91	17	70	49

This technique was also applied successfully to the treatment of NSTL's chemical wastewaters (6). A new system in a zig zag configuration was constructed with the following dimensions: surface area, 0.22 ha; length, 332 m; width, 6.4 m; maximum depth, 0.78 m; total volume, 1,041 m³. The canal received 95 m³/day of water contaminated with photographic and chemical wastewater. Table 3 contains the average water quality of the system during its first year of operation. This system is still effectively operating to date with a slightly increased influent flow rate of 114 m³/day.

TABLE 3. MEAN WATER QUALITY OF NSTL CHEMICAL WASTE SYSTEM DURING FIRST YEAR OF OPERATION.[6]

PARAMETER	CONCENTRATION, mg/l INFLUENT	EFFLUENT
BOD_5	113	3
COD	384	42
TOC	71	17
TDS	605	283
TSS	8	14

The cost effectiveness, efficiency, and environmental advantages of using aquatic plants for treating wastewaters at NSTL during the past several years has resulted in continuous support by NASA in seeking other beneficial uses of higher plants. Current studies at NSTL are directed toward determining the degree of nutrient recycling that can be achieved following the anaerobic digestion of plant biomass to produce methane. The degree in which mineral residue from energy production can be reused as fertilizer is important in reducing the cost of energy farms. The potential for combining waste treatment and energy production systems where nutrients from both sewage and anaerobic digesters are recycled through plant biomass is demonstrated in the following productivity and plant conversion data.

Projected Productivities of Candidate Plant Species

The primary candidate for aquatic energy farming and waste treatment in the sub-tropical United States is, of course, the water hyacinth. The wetland plant species presently studied by NASA which has a high potential productivity is the cattail (Typhaceae). Boyd (7) measured maximum cattail (Typha latifolia) growth rates of 52.6 g dry weight/m^2/day. Pratt and Anderson (8) found that the cattail could produce approximately 40 g dry weight/m^2/day during the period of maximum production. An average value of 46.3 g/m^2/day was used in Table 4 to determine the projected annual productivity of the cattail in south Mississippi during a normal growing season. Projected mean daily and annual productivities of these two plant species are compared in Table 4. When water hyacinth and cattail are cultivated in a controlled manner with regular fertilization and optimal harvesting rates, annual productivities of 154 (9) and 97 t/ha, respectively, are projected based on at least a seven month growing season. Annual projected productivities exceeding 100 t/ha are not unrealistic for plants cultivated under ideal conditions to achieve constant maximum biomass production. Projections of this magnitude have been cited by other authors for a variety of plants such as chlorella, sugar cane, sorghum, and water hyacinth (10,11,12).

TABLE 4. MEAN DAILY PRODUCTIVITY AND PROJECTED POTENTIAL ANNUAL PRODUCTIVITIES

	Mean Productivity, t(dry weight)/ha			
	Daily		Annual*	
Plant	Total Biomass	Volatile Solids	Total Biomass	Volatile Solids
Water hyacinth	0.71	0.60	154	131
Cattail**	0.46	0.40	97	84

* Based on a 7-month growth period in south Mississippi
** Aerial portion only

Biogas Production

The biomass produced on energy farms can be used as a substrate for anaerobic fermentation to produce biogas containing approximately 60% methane by volume. NASA has been using a new "anaerobic filter" technique to produce biogas in an average of three weeks (13). The anaerobic filter provides a large surface area for permanent microbial attachment, maintains an anaerobic bacterial population in a separate vessel to minimize oxygen contact, and reduces the lag time and total fermentation time for methane generation. The efficiency of the filter improves with age until maturation is reached, when the mixed microbial population attains an optimal balance as demonstrated in Figure 1. Example data of batch biodigestions with and without a mature anaerobic filter can be compared in Table 5. Based on the data presented in Table 5, a mean methane volume of 0.21 m^3/kg dry weight (3.4 cu.ft./lb) was produced in three weeks. In batch fermentations without the aid of an anaerobic filter, the batch digestion time for fresh plant material is four to five times greater.

The plant material used in the studies compared in Table 5 as well as cattail biomass fit the general requirements for good potential substrate material for anaerobic digestion as shown in Table 6. These general requirements include high volatile solids, high content of carbonaceous constituents especially fat, protein, sugars, and lipids followed by hemicellulose and lastly cellulose, low lignin content, and a carbon to nitrogen ratio $\leq$ 30:1.

TABLE 5. BATCH FERMENTATIONS WITH AND WITHOUT ANAEROBIC FILTER (AF) AT 36°C. (All gas volumes corrected to 20°C, and all masses reported on a dry weight basis.)[13,14]

	WITH AF			WITHOUT AF
Parameter	WH	WH/DW MIX	KZ/DW MIX	WH
Total biogas,				
m^3/kg	0.356	0.381	0.366	0.245
ft^3/lb	5.71	6.11	5.93	3.93
Total methane,				
m^3/kg	0.198	0.215	0.214	0.169
ft^3/lb	3.17	3.45	3.47	2.71
Overall % methane	56	56	59	69
Digestion time, day	22	21	21	103

WH - water hyacinth
DW - duckweed
KZ - kudzu

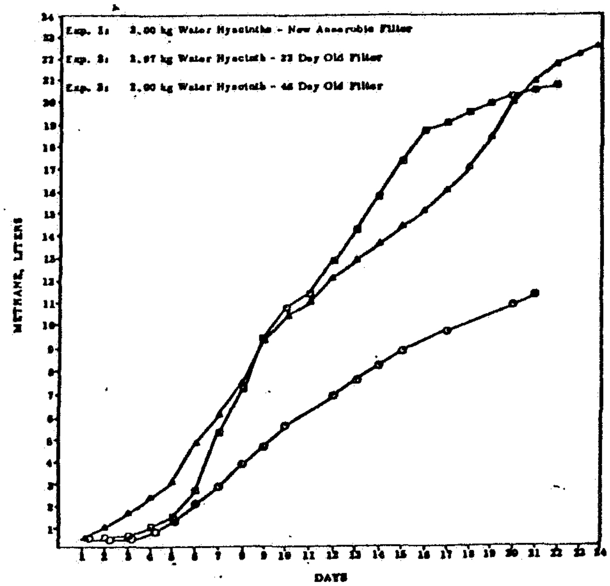

Figure 1. Comparison of Water Hyacinth Digestion Rates and Anaerobic Filter Age.

TABLE 6. MAJOR CONSTITUENTS OF PLANT BIOMASS SUITABLE FOR ANAEROBIC DIGESTION.[5,13]

	Content, % Dry Weight			
Constituent	Water hyacinth	Cattail*	Duckweed	Kudzu*
Volatile solids	88.9	86.6	87.5	91.8
Fat	1.59	3.12	3.40	2.11
Fiber	18.6	26.3	15.6	31.3
Crude protein	14.7	18.4	37.0	16.3
Cellulose	21.5	26.2	10.0	26.2
Hemicellulose	33.9	40.4	21.7	20.8
Lignin	6.01	5.97	2.72	10.5
Carbon	39.9	50.1	43.7	43.1
Nitrogen	2.35	2.95	5.92	2.61
C:N	17:1	17:1	7:1	17:1

*Aerial portion only

Nutrient Recycling

During anaerobic fermentation, gaseous products are evolved. Methane and carbon dioxide are the main components of biogas with small amounts of nitrogen, hydrogen sulfide, and hydrogen. Using the information in the previous section and assuming that only insignificant volumes of gases other than carbon dioxide are lost, then 40% of the initial substrate mass is lost in the gaseous state, and the remaining minerals are concentrated by a factor of 1.7. The organic fertilizer that remains is completely stabilized and ready for immediate reuse. The small amounts of nitrogen and sulfur that are lost are replenished by the wastewater if the system serves a dual purpose for waste treatment and biomass production; otherwise a small, supplemental addition of commercial fertilizer may be necessary. Other possible nitrogen supplemental sources are legumes which fix atmospheric nitrogen. One potential candidate plant for this purpose is the kudzu vine ([illegible]) which is noted for its hardiness and [illegible] as well a [illegible] qualities when allowed to grow freely. Current research efforts by NASA at NSTL are directed toward balancing such a nutrient recycling and bio-conversion system.

Projections

Based on the projected productivities of the water hyacinth and cattail, one hectare of each plant species could generate enough biomass annually to produce 32,300 and 20,400 m^3 methane, respectively. The heat content of the energy produced per hectare would be 1.24×10^6 MJ for the water hyacinth system and 0.79×10^6 MJ for the cattail system. Metric-english conversions are shown in Table 7.

TABLE 7. ENERGY PRODUCTION POTENTIAL OF WATER HYACINTH AND CATTAIL

	Methane		Energy Content	
Plant	m^3/ha/yr	scf/ac/yr	MJ/ha/yr	BTU/ac/yr
Water hyacinth	32,300	462,000	1.24×10^6	476×10^6
Cattail	20,400	292,000	0.79×10^6	301×10^6

One must note at this point that these energy production values are "gross" and not "net" values. Candidate plants from each of the three categories - aquatic, wetland, and terrestrial - must be considered in order to evaluate each respective plant's ease of maintenance, fertilization, harvesting, collection, and transportation. Although the gross productivity and consequently gross energy production may be extremely high, the net energy production may be lower than another plant species due to the energy input requirements.

Figure 2 shows an artist concept of a comprehensive energy system. Alcohol is also an integral part of this biomass conversion concept. The residual sludge in the anaerobic digesters would be partially dewatered and the mineral rich liquids returned as plant fertilizer. Following pretreatment, the undigested cellulose would be fed into a fermenting vat containing cellulase enzyme and brewers yeast. The cellulose is first converted to sugars and then to alcohol (15). The alcohol would be distilled by using energy from the solar hot water system and supplemental heat, if needed, from methane.

METHANE-ETHANOL ENERGY CONVERSION SYSTEM

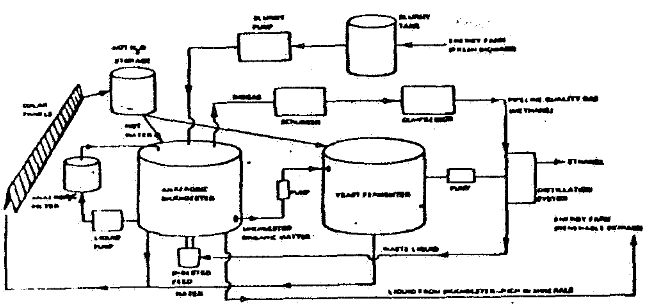

FIGURE 2

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